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VIII.

AN EMPIRICAL RULE FOR CONSTRUCTING TELEPHONE CIRCUITS.

By William W. Jacques.

Presented June 15, 1887.

The following paper describes some investigations I have made as to the proper dimensions to be given to pole lines and cable conductors, in order that they shall be best fitted to transmit speech telephonically.

The experiments were made by selecting cables varying in size of conductor, thickness of insulating coating, and material used for insulating, and measuring in each case the greatest length in miles through which good business conversation could be carried on.

Similar experiments were then made with pole lines, in which the size of the wire was varied, the distance it was suspended above the earth was varied, and both iron and copper wires were used.

Further experiments were then made in which mixed cable and pole lines were used, varying the proportionate length of cable to pole line in each case, and also the position of the cables in the line.

These experiments were made upon a large number of underground cables, varying in length from one mile to one hundred miles, in resistance per mile from 2.8 ohms to 48.0 ohms and in electro-static capacity per mile from 0.11 microfarad to 0.35 microfarad, in use in France and Germany, (an abstract of which was published in the Proceedings of the Society of Arts of November 13, 1884,) and were continued upon a large number of cables and pole lines in our own country.

The method of experiment was to connect up varying lengths of cable or pole line until the greatest length at which it was possible to transmit good business conversation was reached, and then to measure the electrical resistance and capacity of the circuit.

Some of the experiments are given in Tables I. to IV., to illustrate the method of experiment, and prove the results stated later.

TABLE I. — Experiments on Cables.

	Length in Miles.	Resistance per Mile in Ohms.	Capacity per Mile in Microfarads.	Total Resistance.	Total Capacity.	Product of total Resistance by total Capacity.	Quality of Talking.	
							Blake.	Hunnings.
Paris Telephone Wires.	5	48	0.16	240	0.80	192	Good talking.	Good talking.
" " "	10	48	0.16	480	1.60	768	" "	" "
" " "	15	48	0.16	720	2.40	1,728	" "	" "
" " "	20	48	0.16	960	3.20	3,072	Experts could talk.	" "
" " "	30	48	0.16	1,440	4.80	6,932	Could not talk.	Experts could talk.
" " "	35	48	0.16	1,680	5.60	9,408	" " "	" " "

TABLE II. — Experiments on Cables.

	Distance in Miles.	Resistance per Mile in Ohms.	Capacity per Mile in Microfarads.	Total Resistance.	Total Capacity.	Product of total Resistance by total Capacity.	Quality of Talking.	
							Blake.	Hunnings.
Paris and Orleans (Gov. Telegraph).	85	13.3	0.07	1,131	5.95	6,729	Could not talk.	Experts could talk.
" " "	85	8.6	0.11	731	9.35	6,835	" " "	" " "
" " "	85	4.3	0.20	365	17.0	6,189	" " "	" " "
" " "	85	2.87	0.31	244	26.35	6,429	" " "	" " "
Paris and Soissons.	65	9.6	0.06	624	3.90	2,434	" " "	Good talking.
" " "	65	16.0	0.05	1,040	3.25	3,380	Experts could talk.	" "
German Cables.	31	12.1	0.35	375	10.85	4,069	Could not talk.	" "

TABLE III. — Experiments on Pole Lines.

	Distance talked in Miles.	Resistance per Mile in Ohms.	Capacity per Mile in Microfarads.	Total Resistance.	Total Capacity.	Product of total Resistance by total Capacity.	Quality of Talking.	
							Blake.	Hunnings.
Boston and New York, Copper.	300	5	.012	1,500	3.6	5,400	Could not talk.	Experts could talk.
Boston and Providence, Copper.	52	5	.012	260	.624	162	Good talking.	Good talking.
Boston and New Haven, Copper.	191	5	.012	955	2.8	2,674	Experts could talk.	" "
Boston and Providence, Iron.	52	19.6	.015	1,020	.78	796	Good talking.	" "
Boston and Newburyport, Iron.	50	20	.017	1,000	.9	900	" "	" "
Boston and Rye Beach, Iron.	80	20	.018	1,600	1.5	2,400	Only experts could talk.	" "
Boston and New Haven, Iron.	191	20	.017	3,820	3.25	12,600	Could not talk.	Could not talk.

TABLE IV. — Mixed Cable and Pole Lines.

	Miles of Cable.	Miles of Poles.	Resistance per Mile of Cable.	Resistance per Mile of Pole Wire.	Capacity per Mile of Cable.	Capacity per Mile of Pole Wire.	Total Resistance of Cable.	Total Resistance of Pole Wire.	Total Capacity of Cable.	Total Capacity of Pole Wire.	Product of total Resistance by total Capacity.	Quality of Talking.	
												Blake.	Hunnings.
Block Island Line.	12	20	12.9	16.1	.35	.021	155	322	4.20	.42	2,204	Experts could talk.	Good talking.
Pittsburg (Standard Star).	$2\frac{1}{2}$	30	25	. . .	.46	.013	63	1465	1.15	.39	2,353	" " "	Good talking.
Pittsburg (Patterson).	$2\frac{1}{2}$	30	25	. . .	.29	.013	63	1465	.73	.39	1,711	Good talking.	Good talking.
Attleborough.	5	$1\frac{1}{2}$	58	19.6	.33	.014	290	29.4	1.65	.021	535	" "	
"	10	$1\frac{1}{2}$	58	19.6	.33	.014	580	29.4	3.30	.021	2,024	Experts could talk.	
"	15	$1\frac{1}{2}$	58	19.6	.33	.014	870	29.4	4.95	.021	4,469	Could not talk.	
"	5	13	58	19.6	.33	.014	290	255	1.65	.182	815	Good talking.	
"	10	13	58	19.6	.33	.014	580	255	3.30	.182	2,906	Could not talk.	

Tables I. and II. give the results of some experiments made on cables; Table III., on pole lines; and Table IV., on mixed cables and pole lines. The numbers showing the total resistance and total capacity refer to the line between the terminal instruments, and do not include the terminal instruments.

I find from these experiments, that the readiness with which telephonic conversation may be carried on over any circuit, whether made up of cables or pole lines, or both, depends, —

1. On the total electrical resistance of the circuit joining together the two stations.

2. On the total electrostatic capacity of this circuit.

So long as the insulation is sufficiently good to prevent any considerable loss of current, its actual value, whether high or low, does not affect the readiness with which conversation may be carried on. High insulation is desirable, however, when two or more wires run near together, in order to prevent extraneous currents from leaking in and causing disturbing noises.

The distance over which telephonic conversation may be carried on, being thus dependent on the resistance of the circuit and on the capacity of the circuit, (being inversely proportional to each of these,) is dependent upon their product, and this product has a definite numerical value for each kind of transmitter used, being 4,500 for transmitters of the Hunnings type, and 2,000 for transmitters of the Blake type; that is, the product of the total resistance of the current between two telephones, by its total capacity, must not exceed 4,500 if transmitters of the Hunnings type be used, and must not exceed 2,000 if transmitters of the Blake type be used. These results suppose the ordinary Bell hand telephone to be used as a receiver, but are not essentially varied by the use of other good forms of magneto receiver. These limits are given for good business conversation. It is of course possible for experts to get messages through circuits the product of whose resistance and capacity is somewhat greater than this.

The resistance and capacity measured should be, as stated, that of the line between the two telephones. It includes, of course, the resistance and capacity of any way station switchboards or call bells. It does not include the resistances of the terminal telephone instruments used.

These results may be briefly formulated in the following rule: —

"No matter what may be the distance between two points, good business conversation may be carried on between them, provided they be connected by a pole line or cable, or both, the product of whose total resistance by its total capacity is less than 2,000 if transmitters of the Blake type be used, and less than 4,500 if transmitters of the Hunnings type be used."

This rule is purely the result of experiment. It applies to a single conductor joining together the two telephones, and is equally applicable whether the return circuit is completed through the earth or by means of a second wire similar and parallel to the first. It supposes the line to be ordinarily free from extraneous noises, and, as in positions especially liable to extraneous noises metallic circuits would naturally be used, it is in all cases a perfectly safe working rule.

Having thus determined the general rule above annunciated, we must be able to apply it to specific cases; as, for example, to write a specification for a line which is to connect two cities one hundred miles apart, and which is to pass from the centre of each city underground, two miles, to the suburbs.

In order to do this, we need to know the resistance per mile of various sizes of wire, whether of iron or copper, and excellent tables are published in various text-books giving these figures. I have, for convenience, printed the resistances of various sizes of iron and copper wire in the annexed Tables V. and VI.

TABLE V. — IRON WIRE.

No. B. W. G.	Diameter in Inches.	Ohms per Mile.	Feet per Mile.
0000	.454	1.70	3106
000	.425	1.95	2708
00	.380	2.43	2172
0	.340	3.83	1378
1	.300	3.91	1350
2	.284	4.36	1211
3	.259	5.24	1008
4	.238	5.51	958
5	.220	7.26	727
6	.203	8.54	618
7	.180	10.86	578
8	.165	12.92	409
9	.148	16.10	328
10	.134	19.60	269
12	.109	29.60	179
14	.083	51.00	104
16	.065	83.20	63
18	.049	147.00	35.9

TABLE VI. — Copper Wire.

No. B. W. G.	Diameter in Inches.	Ohms per Mile.	Feet per Mile.
5	.220	1.128	4681
6	.203	1.325	3986
7	.180	1.684	3135
8	.165	2.005	2634
9	.148	2.492	2120
10	.134	3.040	1737
11	.120	3.791	1393
12	.109	4.594	1149
13	.095	6.048	873
14	.083	7.936	665
15	.072	10.529	502
16	.065	12.918	408.7
17	.058	16.99	310.8
18	.049	22.73	232.3
19	.042	30.94	170.6
20	.035	44.55	118.5
22	.028	69.62	75.8
24	.022	112.77	46.8

But we need also to know the capacity per mile of various sizes of pole wire when suspended at various heights above the earth, (for the capacity of a pole wire depends both upon its size and the distance it is suspended above the earth,) and we need further to know the various capacities of various sizes of cable conductors when insulated to various thicknesses, and when insulated with various substances; for the capacity of a cable conductor depends upon its size, upon the distance it is removed from neighboring conductors by the thickness of the insulating coating, and upon the specific inductive capacity of the particular insulating coating used.

Now the available data regarding capacities of pole lines and of cables (excepting ocean telegraph cables which have only one conductor, and in which the conductors are quite different from that of the multiple conductor cables used in telephony) are very meagre, and I have therefore been obliged to undertake an experimental investigation into the capacities of wires of different sizes, suspended on poles of varying heights, and a further investigation into the capacities of various sizes of cable conductors when separated from the neighboring conductors by varying thicknesses of insulating material, and when insulated with various materials differing in specific inductive capacity.

The results are given in Tables VII., VIII., and IX.

TABLE VII. — Capacities of Pole Wires.

No. B. W. G.	Diameter in Inches.	Height of Pole in Feet.										
		20.	22.	24.	26.	28.	30.	32.	34.	36.	38.	40.
0000	.454	.0149	.0147	.0145	.0144	.0143	.0142	.0141	.0139	.0138	.0137	.0136
000	.425	.0148	.0146	.0144	.0143	.0142	.0141	.0140	.0138	.0137	.0136	.0135
00	.380	.0147	.0144	.0143	.0141	.0140	.0138	.0137	.0136	.0135	.0135	.0134
0	.340	.0144	.0141	.0141	.0139	.0138	.0136	.0135	.0135	.0134	.0133	.0132
1	.300	.0142	.0140	.0138	.0137	.0136	.0135	.0134	.0133	.0132	.0131	.0130
2	.284	.0140	.0139	.0137	.0136	.0135	.0134	.0133	.0132	.0131	.0130	.0129
3	.259	.0139	.0137	.0135	.0135	.0134	.0132	.0130	.0130	.0129	.0129	.0128
4	.238	.0137	.0136	.0134	.0134	.0132	.0131	.0129	.0129	.0128	.0127	.0127
5	.220	.0136	.0135	.0133	.0132	.0131	.0130	.0127	.0128	.0127	.0126	.0126
6	.203	.0135	.0134	.0132	.0131	.0130	.0128	.0126	.0127	.0126	.0125	.0125
7	.180	.0133	.0132	.0130	.0129	.0128	.0127	.0125	.0125	.0125	.0124	.0123
8	.165	.0131	.0131	.0129	.0127	.0127	.0126	.0123	.0124	.0123	.0122	.0122
9	.148	.0130	.0128	.0127	.0126	.0125	.0125	.0122	.0122	.0122	.0121	.0120
10	.134	.0128	.0127	.0126	.0125	.0124	.0123	.0120	.0121	.0120	.0119	.0119
12	.109	.0126	.0124	.0123	.0122	.0121	.0120	.0116	.0119	.0118	.0118	.0117
14	.083	.0122	.0120	.0120	.0119	.0118	.0117	.0113	.0115	.0115	.0114	.0113
16	.065	.0119	.0118	.0117	.0116	.0115	.0114	.0113	.0112	.0112	.0112	.0111
18	.049	.0115	.0114	.0113	.0112	.0111	.0111	.0110	.0110	.0109	.0108	.0108

TABLE VIII. — CAPACITIES. GUTTA-PERCHA CABLES.

(Spf. Ind. Capacity = 4 2.) $C = \dfrac{0.1628}{\log \dfrac{2d + 4T}{d}}$.

Number of Conductor in B.W.G.	Diameter of Conductor in Inches (= *d*).	Thickness of Insulating Coating in Inches (= *T*).													
		.01.	.02.	.03.	.04.	.05.	.06.	.07.	.08.	.09.	.10.	.12.	.15.	.20.	.25.
1	.300	.496	.457	.429	.404	.382	.364	.349	.334	.324	.312	.293	.270	.243	.224
2	.284	.493	.454	.424	.399	.378	.359	.343	.329	.317	.306	.287	.265	.238	.219
3	.259	.490	.448	.416	.389	.368	.349	.333	.324	.307	.299	.278	.256	.230	.212
4	.238	.484	.441	.409	.382	.359	.341	.324	.311	.298	.288	.269	.249	.225	.206
5	.220	.481	.437	.402	.373	.352	.332	.317	.303	.290	.279	.262	.241	.217	.200
6	.203	.476	.430	.389	.365	.342	.313	.308	.294	.283	.271	.255	.234	.210	.194
7	.180	.470	.421	.382	.353	.330	.311	.296	.283	.270	.260	.244	.224	.201	.185
8	.165	.465	.413	.373	.344	.317	.332	.287	.273	.262	.252	.236	.217	.195	.180
9	.148	.457	.402	.363	.333	.310	.291	.276	.263	.252	.242	.226	.208	.187	.173
10	.134	.454	.394	.353	.307	.299	.286	.266	.254	.243	.234	.218	.201	.180	.167
12	.109	.438	.373	.332	.301	.279	.265	.246	.235	.225	.216	.202	.186	.168	.155
14	.083	.413	.346	.303	.263	.253	.236	.222	.212	.203	.195	.183	.169	.153	.142
16	.065	.390	.320	.279	.251	.231	.216	.203	.194	.186	.179	.168	.155	.141	.131
18	.049	.361	.291	.251	.226	.208	.194	.184	.175	.165	.162	.152	.142	.129	.120
20	.035	.328	.261	.221	.199	.183	.172	.162	.156	.149	.144	.136	.127	.117	.109
22	.028	.304	.237	.204	.181	.169	.159	.151	.144	.139	.134	.127	.119	.109	.103

TABLE IX. — Capacities. India Rubber Cables.

(Spf. Ind. Capacity = 3.7.)

Number of Conductor in B. W. G.	Diameter of Conductor in Inches (= *d*).	Thickness of Insulating Coating in Inches (= *T*).													
		.01.	.02.	.03.	.04.	.05.	.06.	.07.	.08.	.09.	.10.	.12.	.15.	.20.	.25.
1	.300	.436	.402	.378	.356	.336	.320	.307	.294	.285	.275	.258	.238	.214	.197
2	.284	.434	.400	.373	.351	.333	.316	.302	.290	.279	.269	.253	.233	.209	.193
3	.259	.431	.394	.368	.342	.324	.307	.293	.285	.270	.263	.245	.225	.202	.187
4	.238	.426	.388	.360	.336	.316	.300	.285	.274	.262	.253	.237	.219	.198	.181
5	.220	.423	.385	.354	.328	.310	.292	.279	.267	.255	.246	.231	.212	.191	.176
6	.203	.419	.378	.342	.321	.301	.275	.271	.259	.249	.238	.224	.206	.185	.171
7	.180	.414	.370	.336	.311	.290	.274	.260	.249	.238	.229	.215	.197	.177	.163
8	.165	.409	.366	.326	.303	.279	.266	.253	.240	.231	.222	.208	.191	.172	.158
9	.148	.402	.353	.317	.293	.273	.256	.243	.231	.222	.213	.199	.183	.165	.152
10	.134	.400	.347	.309	.270	.263	.252	.234	.224	.214	.196	.192	.177	.158	.147
12	.109	.385	.328	.290	.265	.246	.233	.217	.207	.198	.190	.178	.164	.148	.136
14	.083	.363	.304	.265	.231	.223	.208	.196	.187	.179	.172	.161	.149	.135	.125
16	.065	.343	.282	.246	.221	.203	.190	.179	.171	.164	.158	.148	.136	.124	.115
18	.049	.318	.256	.221	.199	.183	.171	.162	.154	.145	.143	.134	.125	.114	.106
20	.035	.289	.230	.194	.175	.161	.151	.143	.137	.139	.127	.120	.112	.103	.096
22	.028	.268	.209	.180	.159	.149	.140	.133	.127	.122	.118	.112	.105	.096	.091

TABLE X. — Capacities. Paraffine Cables.

(Spf. Ind. Capacity = 2.52.)

Number of Conductor in B. W. G.	Diameter of Conductor in Inches (= *d*).	Thickness of Insulating Coating in Inches (= *T*).													
		.01.	.02.	.03.	.04.	.05.	.06.	.07.	.08.	.09.	.10.	.12.	.15.	.20.	.25.
1	.300	.298	.274	.257	.242	.229	.218	.209	.200	.194	.187	.176	.162	.146	.134
2	.284	.296	.272	.254	.239	.227	.215	.206	.197	.190	.184	.172	.159	.143	.131
3	.259	.294	.269	.250	.233	.221	.209	.200	.194	.184	.179	.167	.154	.138	.127
4	.238	.290	.265	.245	.229	.215	.205	.194	.187	.179	.173	.161	.149	.135	.124
5	.220	.289	.262	.241	.224	.211	.199	.190	.182	.174	.167	.157	.145	.130	.120
6	.203	.286	.258	.233	.219	.205	.188	.185	.176	.170	.163	.153	.140	.126	.116
7	.180	.282	.253	.229	.212	.198	.187	.175	.170	.162	.156	.146	.134	.121	.111
8	.165	.279	.248	.224	.206	.190	.180	.172	.164	.157	.151	.142	.130	.117	.108
9	.148	.274	.241	.218	.200	.186	.175	.166	.158	.151	.145	.136	.125	.110	.104
10	.134	.272	.236	.212	.184	.179	.172	.160	.152	.146	.140	.131	.121	.108	.100
12	.109	.263	.224	.199	.181	.167	.159	.148	.141	.135	.130	.121	.112	.101	.093
14	.083	.248	.208	.182	.158	.152	.142	.133	.127	.122	.117	.110	.102	.092	.085
16	.065	.234	.192	.167	.151	.139	.130	.122	.116	.112	.108	.101	.093	.085	.079
18	.049	.217	.175	.151	.136	.125	.116	.110	.105	.099	.097	.091	.085	.079	.072
20	.035	.197	.157	.133	.119	.110	.103	.097	.094	.089	.086	.082	.076	.070	.065
22	.028	.182	.142	.122	.109	.101	.095	.091	.086	.083	.080	.077	.071	.067	.062

Table VII. gives the capacities of wires from No. 0000 B. W. G. to No. 18, when suspended above the ground at heights varying from 20 feet to 50 feet.

Of course I have not measured the capacity of each size of wire at each height, but I have chosen a large variety of sizes and heights, and, having measured these, have calculated the remainder from these by means of the formula

$$C = \frac{k\,l}{\log \frac{4\,h}{d}},$$

in which

C = capacity of the lines in microfarads.
l = length of line in miles.
h = height above the earth in inches.
d = diameter of lines in inches.
k = the number .0496, i. e. the capacity of such a wire that $\frac{l}{\frac{\log 4\,h}{d}}$ = unity; this number (k) being calculated from such wires as were actually measured.

The capacity of any wire not given in the table may be calculated from this formula.

The capacities thus obtained apply to a single wire on a line of poles. If there are other wires on the same poles, a correction must be added depending upon the number of such wires, and their distance apart.

For the ordinary case we meet with in telephony — i. e. a considerable number and placed about 18 inches apart — a sufficiently accurate correction may be obtained by adding 50%.

Table VIII. gives the capacities of different sizes of wire from No. 4 to No. 22 B. W. G., when insulated with successive thicknesses of gutta-percha from .01 inch to .25 inch, and combined into cables of fifty conductors and enclosed in a metallic sheath.

Table IX. is a similar table, in which India-rubber is used for insulating; and Table X. one in which the conductors of the cable are insulated with cotton so impregnated with paraffine as to be homogeneous. This table is applicable to the so-called Patterson cable if the values be increased by 60%.

These tables were prepared by measuring a wide variety of cable conductors differing in size of conductor, thickness of insulating material, and kind of insulating material, and calculating the remaining values from the measured values by the formula

$$C = \frac{N L I}{\frac{\log 2s}{d}} = \frac{N L I}{\frac{\log 2d + 4T}{d}},$$

in which

C = capacity of the conductor in microfarads.
s = average distance between centres of adjacent conductors.
d = diameter of conductor.
T = thickness of insulating coating of any one conductor.
L = length of conductor in miles.
I = specific inductive capacity of insulating material used.
N = the number 0.0387, i. e. the capacity of one mile of such a wire that $\frac{I}{\frac{\log 2s}{d}}$ = unity.

The number N is calculated from values reached by experiments on a large number of conductors.

The capacity of any cable conductor not given in these tables, and insulated with any material whose specific inductive capacity is known, may be calculated from this general rule.

Having thus determined a general rule for the construction of any telephone circuit, and having provided in the foregoing tables data by which the rule may be applied, I will give an illustration, by applying it to the particular case above cited, namely a telephone line between two cities one hundred miles apart, entering each city by underground cables two miles in length.

Let us further suppose that the subscriber is in each case connected to the central office by a mile of underground cable, and that at each central office, there is a multiple switchboard, any connection through which has a resistance of 25 ohms, and a static capacity of .10 microfarad.

It is desired to use Blake transmitters.

Resistance.

	Ohms.
Line of No. 13 copper on 30 ft. poles, 6.048 × 96 . . .	571
Cable of No. 18 insulated with kerite to No. 10, 22.7 × 6 .	136
Switchboard	25
Total resistance	732

Capacity.

	Mf.
Line of No. 13 copper on 30 ft. poles (.0119 × 96 × 1.5)	1.71
Cable of No. 18 insulated with kerite to No. 10, .15 × 6 .	.90
Switchboard	.10
Total capacity	2.71

Product of total resistance by total capacity = 732 × 2.71 = 1984.

If this line be reasonably free from extraneous noises, it will allow of good business conversation with Blake transmitters. If, however, it should be found to be a noisy line, we should have to return it by means of a similar and parallel line, making a metallic circuit, instead of through the earth.

It is evident that, by using a cable of lower capacity and resistance, we could have used a smaller pole wire, or, by choosing a larger pole wire, we could have used a cable of greater resistance and capacity.

It is also evident that our formula enables us to say which of these alterations will give us the desired ease of conversation at the minimum expense.